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# A preliminary study of dynamic failures in laboratory tests

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# A PRELIMINARY STUDY OF DYNAMIC FAILURES IN LABORATORY TESTS

Qiyu Wang<sup>1</sup>, Chengguo Zhang and Ismet Canbulat

**ABSTRACT:** Sudden and dynamic failure of rock/coal mass during mining is a serious threat to safety in underground mines. This failure is often referred to as 'rockbursts' or 'coal bursts', mainly attributable to high level of stress. In order to investigate the coal burst phenomenon, a series of laboratory tests were conducted to examine the failure patterns associated with a burst event. Optical glass cube samples were drilled under varying stress conditions, to investigate the influence of stress environment on the dynamic failure. The outcomes of these laboratory tests will improve the understanding of the loading mechanisms leading to coal burst, especially the influence of high stress environment.

## INTRODUCTION

Coal bursts are a major threat to mining safety in underground mines, especially for workings at great depth. Potvin and Wesseloo (2013) stated that the possibility of experiencing a seismic event resulting in fatalities has arguably become the most important financial (and safety) risk in underground hard rock mines operating in developed countries.

In traditional laboratory tests of dynamic failures of rock/coal samples, it is necessary to stop the test and unload the sample in order to observe the failure patterns. However, the changes that occur within the sample during the unloading process are unknown and cannot be controlled. Accordingly, there is a need for an improved methodology to directly observe dynamic failures under high static loading. The objective of this paper is to study dynamic failures by replacing coal with optical glass in drilling tests (to simulate the mining process) for direct observation of the associated failure patterns by taking the advantage of the high transparency of optical glass. This paper describes the laboratory experiments which simulate the dynamic failures in optical glass by drilling optical glass cubes of 50 mm side length under static loading. The process of dynamic loading is filmed and the tested samples are photographed for further analyses. It is not the intention of this study to extend the findings of this study into *in situ* behaviour of coal burst but rather make observations of some of the established loading and failure mechanisms.

## CAUSES OF COAL BURST

### Geologic factors

Over the years many studies have been conducted into the mechanism of coal bursts. Although the exact causes have never been understood (with any confidence); the following geological factors have been identified as contributors of coal burst by combining *in situ* observations and measurements with computer back-analysis:

- Depth of cover (Holland, 1958; Maleki, 1995; Makeli *et al*, 1999)
- Sandstone channels (Hoelle, 2008; Agapito and Goodrich, 1999; Maleki *et al*, 2011)
- Seam rolling and pitching (Iannacchione and Zelanko, 1995; Maleki *et al*, 2011)
- Faults (Holland, 1958; Holub, 1997; Agapito and Goodrich, 1999; Alber, *et al*, 2008; Swanson *et al*, 2008)

With respect to the depth of cover, the self-weight of the overburden strata is a source of high static stress, which is considered to be the most critical factor in the occurrence of coal bursts. According to

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Agapito and Goodrich (1999), a rule of thumb used in Utah coal mines is that coal burst problems start at a depth of 450 m with strong immediate roof and floor.

### Loading environment and loss of confinement

Essentially, coal is capable of bearing high vertical stress only with the existence of large confining stress. Under such circumstance, non-violent yielding will normally occur when the vertical load is increased to its peak strength, which is the case in a triaxial test. However, during mining or other off-seam seismic events, this confining stress is dissipated suddenly and the strain energy stored in the coal seam is released in a violent manner. Babcock and Bickel (1984) concluded that coal can be made to burst given necessary conditions of stress and constraint. In cases where the strength is largely produced by constraint, the sudden loss of this constraint can initiate the burst. The proposed testing programme somewhat simulates the loss of confinement in a sample by drilling into it.

## TEST SAMPLES AND SETUP

### Sample material selection

Two types of materials were tested in this project: Poly Methyl Methacrylate (PMMA) and K9 optical glass. PMMA is also known as acrylic based resin or Perspex. It is a thermoplastic of light weight and high transparency. It has a significantly high transmitting rate of visible light reaching 92% which is higher than normal glass. Currently, PMMA has been widely used as a substitute for transparent glass taking advantage of its high transparency and mechanical strength. K9 glass is a type of optical borosilicate crown glass manufactured in China. It is normally used in making the prism and optical lenses due to its low cost, high refractive index and high clarity. These two kinds of material are the only two materials that can be purchased from the market satisfying experimental requirements in terms of transparency, sample size, mechanical strength and cost. Semi-transparent materials are not considered in this project due to their influence on fracture observation. Figure 1 shows a comparison between the samples of PMMA (left) and K9 optical glass (right).

Under high levels of loading in a Uniaxial Compressive Strength (UCS) test, plastic deformation is observed for PMMA material in 100 mm size. K9 optical glass showed brittle characteristics that are similar to coal and consequently was chosen to be the material for this project. Figure 2 shows the PMMA sample (left) after a UCS test undertaken in the MTS rock testing machine.



Figure 1: PMMA (left) and K9 glass (right)

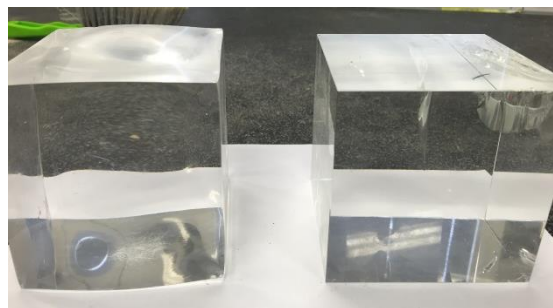


Figure 2: PMMA after UCS test

### Sample size selection

Two different sample sizes of K9 glass, namely 50 mm and 100 mm (in the shape of cubes as illustrated in Figure 3), were evaluated before the experiments. In the UCS test of 100 mm sample, the peak strength of the sample exceeded the limit of the hydraulic loading cell in the MTS testing machine. Therefore, 50mm samples were used in all experiments, which quadruple the stress at the same magnitude of loading.

Figure 4 illustrates the 50 mm sample after a UCS test.



**Figure 3: 50 mm sample (left) and 100 mm sample (right) Figure 4: 50 mm sample after UCS test**

### **MTS rock testing machine**

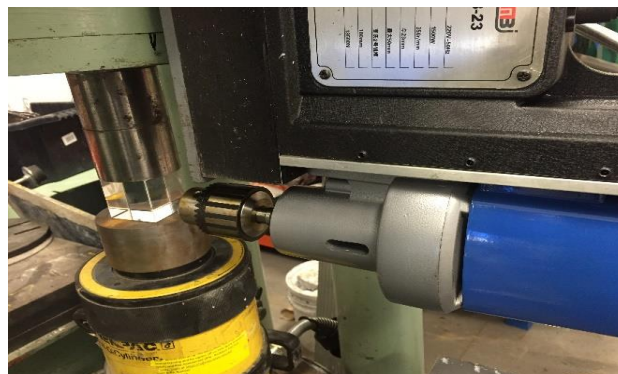
The UCS test is conducted using the MTS rock testing machine, as shown in Figure 5. A consistent loading rate of 0.1mm/s is used in all tests.



**Figure 5: MTS rock mechanics test system**

### **Drill and hydraulic press**

The drill used in the final test is illustrated in Figure 6. The magnetic drill is a specialised power tool used in the drilling of structural steel. It has a strong electromagnetic base enabling it to adhere to a steel surface. The magnetic drill offers increased stability and also provides better accuracy.



**Figure 6: Magnetic drill and hydraulic press**

## Camera

A Sony A6000 camera is used in this project to record the fracturing process within the sample during drilling. In slow motion mode, this camera is able to film 720p footage at a rate of 50 frames per second, which is capable of recording the fast propagation of cracks within samples. A higher speed camera was also evaluated for these experiments. However, due to length of each experiment, the data storage capability of available cameras was exceeded.

## TEST PROCEDURE

### UCS test of intact samples

An intact optical glass sample was first tested to obtain its UCS value prior to drilling tests, as illustrated in Figure 7. In order to ensure the correct loading of the samples, a spherical-seat was used in these experiments as further preparation of samples was impossible. As indicated above, a consistent loading rate of 0.1 mm/s is used in the tests. The results from these tests are summarised in the following sections.

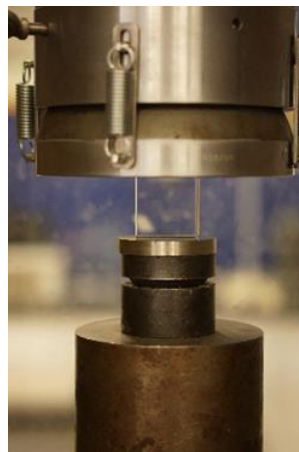


Figure 7: UCS test of intact sample

### UCS test of drilled samples

The second stage of testing was UCS testing of pre-drilled samples. The purpose of the second stage testing was (i) to observe the crack propagation around the borehole and (ii) to determine that the drilled samples fail before they reached the maximum capacity of the hydraulic pump that is used to provide the static loading of samples. The maximum capacity of the pump was 200 kN. The pre-drilled borehole is 12 mm in diameter and 40 mm long. Figure 8 illustrates a drilled 50mm sample in a UCS test.

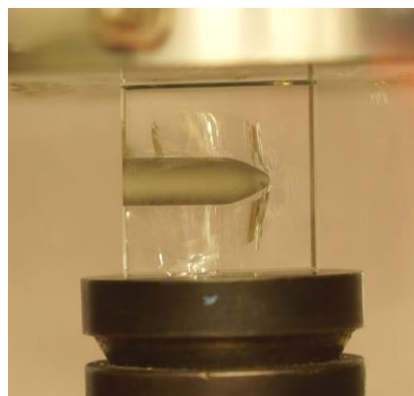


Figure 8: UCS test of a drilled sample

### Loaded drilling test

The tests were undertaken in two different testing frames. The first frame is for 50 mm samples and the second one is for 50 mm x100 mm rectangular samples. In the first frame (Figure 9), the magnetic drill is attached to top steel panel and the drill points to the sample centre. The samples are pre-loaded with different magnitudes of loads starting from 10 kN.



**Figure 9: Final test platform for 50 mm sample**

The second drill frame is shown in Figure 10. The reason for using a different frame is the location of the drill in relation to sample location. When longer samples were used in the first frame the drill bit did not target the middle of the samples; which resulted in imbalance loading of the samples during testing; therefore, the second frame was used for 50 mm x 100 mm rectangular samples.



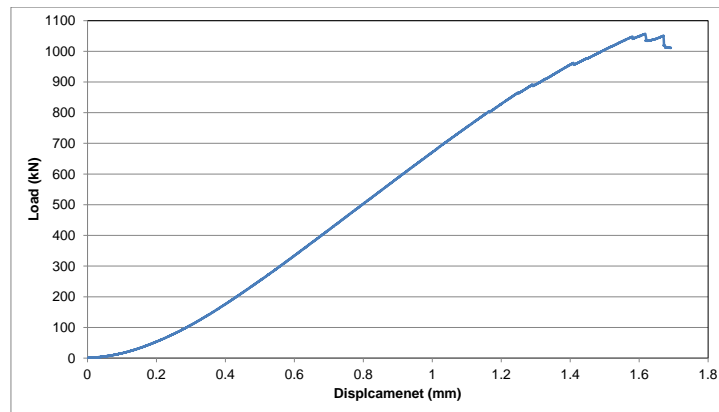
**Figure 10: Final test platform for 100 mm sample**

### TEST RESULTS

#### UCS test results of intact samples

Figure 11 shows the load – displacement curve of a 50 mm sample during a UCS test. The graph indicates that the UCS of the sample is approximately 420 MPa. During the tests it was observed that once the sample reached its maximum strength (and the initial failure occurred) further loading of the sample was possible. However, due to safety reasons the tests were stopped once the samples were loaded up to the maximum strength. Therefore, no post-peak data is available from these tests. It is of note that the UCS of optical glass is not an appropriate parameter to predict cracking in this project as the glass starts to crack at a lower stress which is around 300 MPa.

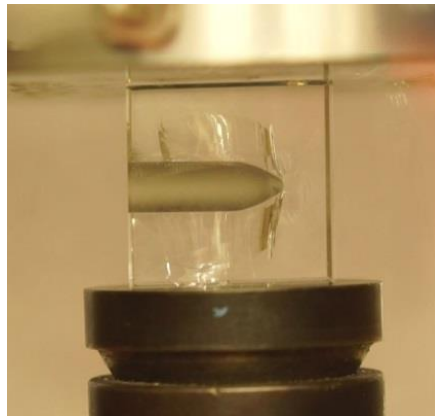




**Figure 11: UCS test result of 50 mm sample**

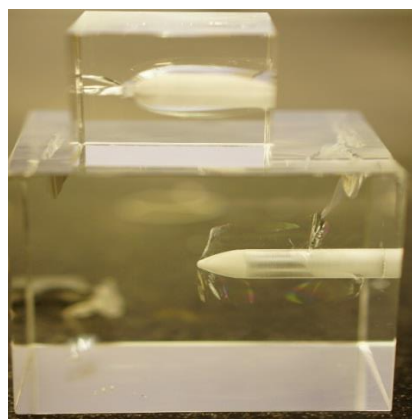
### UCS Test Results of Drilled Samples

The samples used in this test are somewhat different from the intact sample tests presented above. Figure 12 shows a drilled 50 mm sample under loading of 100 kN. The graph indicates that the stress is concentrated around the borehole and leads to the initiation of cracking when the load is increased. As a result, the severity of cracking reveals the level of stress at a particular point.



**Figure 12: 50 mm sample under 100 kN loading**

Figure 13 illustrates a comparison of 50 mm and 100 mm drilled samples. The drill depths of each sample are 40 mm and 50 mm respectively. The 100 mm sample starts to fracture at a much higher stress during the UCS test which exceeds the limit of hydraulic press and consequently, 50 mm is chosen to be the size of test sample for the final tests.



**Figure 13: 50 mm and 100 mm sample**

## LOADED DRILLING TEST RESULT

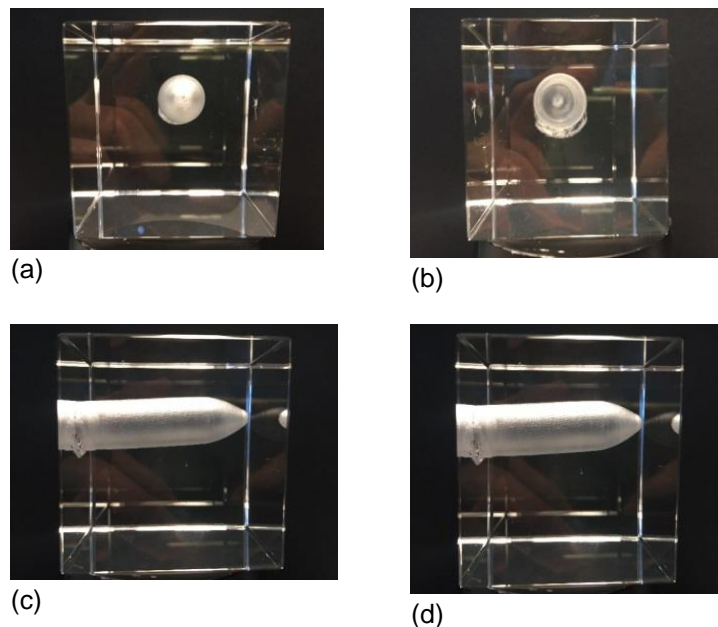
A number of issues arose during the loading of intact samples and these issues cannot be neglected when the magnitude of loading exceeds 160 kN. The issues are summarised as following:

- Point loading on sample surface due to uneven surface of seating
- Irregular increased loading due to manually pumped hydraulic press
- Non-vertical loading due to tilted testing frame

All these issues result in the same problem that the sample fractures to some extent before the drilling stage. The pre-existing cracks influence the occurrence of dynamic failure negatively in such a way that progressive stress induced failure occurs instead of a dynamic failure. Among all of the tests, only four tests were successful with no cracks in the sample before drilling. The uniaxial loading of these four tests are 40 kN, 70 kN, 130 kN and 160 kN respectively. During the final tests, the camera recorded the process of drilling until the occurrence of burst. In order to keep the sample intact for analysis, drilling was stopped once the burst occurred and photos were taken. The result of each test is demonstrated in four different directions: front view, back view, side view and top view.

### Test result at 10 kN

Figure 14 illustrates the test results under 10 kN loading. As clearly shown in the figure, there is no sign of failure, despite the drill reaching the end of the sample. Less than 10 kN loading, the stress on the testing sample is equal to approximately 4 MPa, which is much smaller than the maximum UCS of 420 MPa. This test result indicates the fact that drilling itself will not cause a dynamic failure or fracturing of the sample.

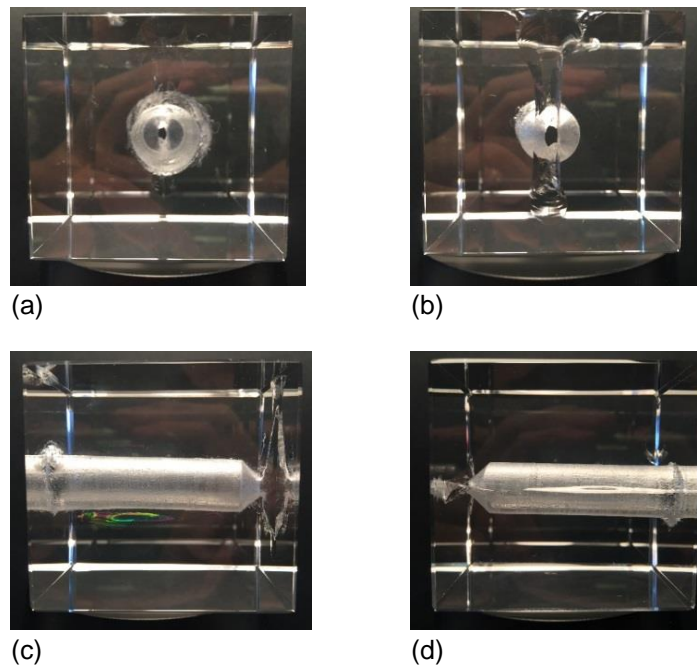


**Figure 14: Test result under 10 kN in (a) front view (b) back view (c) side view (d) top view**

### Test result at 40 kN

Figure 15 illustrates the test result under 40 kN loading. Different from the 10 kN loading, it can be seen from Figure 15(b) that extra damage has occurred to the sample when the sample is drilled through along the direction of loading. However, this cannot be classified as burst because of the gradual failure process during drilling as reviewed in the video.

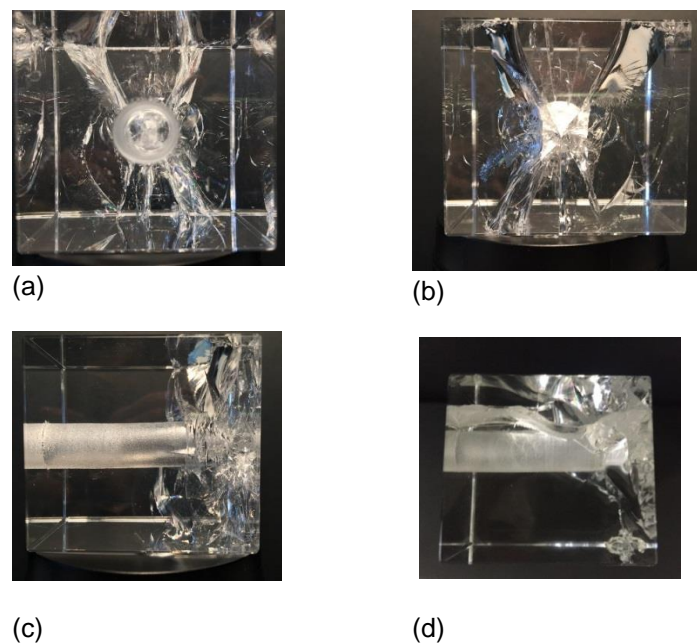




**Figure 15: Test result under 40 kN in (a) front view (b) back view (c) side view (d) top view**

#### **Test result at 70 kN**

Figure 16 illustrates the test result under 70kN of static loading. Under the 70kN loading, dynamic failure occurs before the drill reaches the end of a sample. As can be seen from Figure 16(b), the cracks caused by dynamic failure concentrated around the top of the borehole and radiate out along the direction of uniaxial loading. As is also evident in Figure 16(c) there was no crack around the borehole until dynamic failure occurred.



**Figure 16: Test result under 70 kN in (a) front view (b) back view (c) side view (d) top view**

Due to the pre-existing cracks, tests under 50 kN and 60 kN failed and the test results were not strictly valid. However, it is reasonable to conclude that dynamic failures started occurring once the static

loading is increased to approximately 70 kN, which is approximately 7% of the maximum strength of the K9 glass.

#### Test result at 130 kN

Figure 17 illustrates the test result under 130 kN of static loading. Dynamic failure occurs before drill bit reaches the end of sample and the position is shown in Figure 17(c). Under a higher magnitude of loading, unlike the 70 kN test, the sample starts to crack around the drill hole during drilling as shown in Figure 17(c). This failure somewhat reduces the intensity of the dynamic failure.

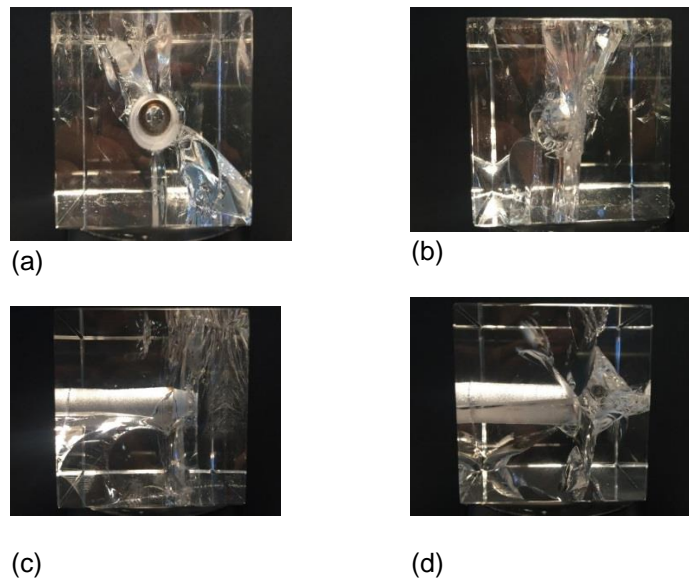


Figure 17: Test result under 130 kN in (a) front view (b) back view (c) side view (d) top view

#### Test result at 160 kN

Figure 18 illustrates the test result under 160 kN of loading. In this experiment dynamic failure occurred as the drilling started and reached the maximum intensity when the drill bit was approximately half way through the sample, which is earlier than the other loading cases.

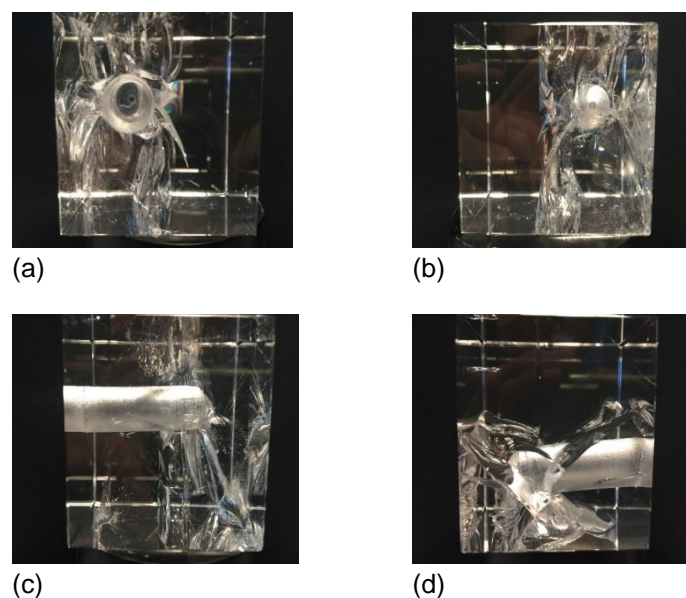


Figure 18: Test result under 130 kN in (a) front view (b) back view (c) side view (d) top view

## ANALYSIS

In the analysis of test results, the following five factors were analysed using the sample pictures and videos:

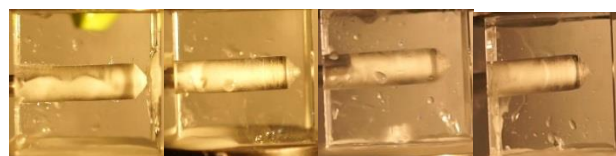
- Stress level
- Burst position
- Timing
- Fracturing pattern
- Drill cutting

### Stress level

As mentioned above, dynamic failure appears to occur at a static pre-loading of approximately 70 kN. The occurrence of a dynamic failure is significantly affected by pre-existing fractures in a way that the pre-existing crack propagates from surface to drill hole during drilling and prevents the sample from failing violently. In this project, only four tests under 40 kN, 70 kN, 130 kN and 160 kN loadings were conducted successfully without pre-existing cracks. When samples with pre-existing cracks were tested under loading higher than 70 kN, the sample failed in a progressive way as cracks initiated from the surface and then merge with the drill hole. The strain energy caused by high stress is gradually released in this process, which prevents occurrence of dynamic failure.

### Dynamic burst position

Along with the high stress environment, another significant factor of dynamic failure is the location of the drill bit with respect to the sample size. Figure 19 illustrates the drill depth at the time of dynamic failure occurrences from the videos recorded. No dynamic failure occurred when the drill bit reached the other end of the sample at 40kN. When load was increased to 70kN in Figure 19(b), the dynamic failure occurred at the position which is nearly at the end of the sample. As loading increases to 130kN and 160kN, dynamic failure position gets closer to the drilling starting point. This can be explained by the fact that the load increases in the intact section of the sample during the drilling process (i.e., pinching of the load) and the higher the initial load the earlier the dynamic failure occurs.

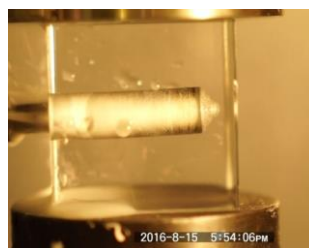


(a) 40 kN    (b) 70 kN    (c) 130 kN    (d) 160 kN

**Figure 19: Burst position within test samples**

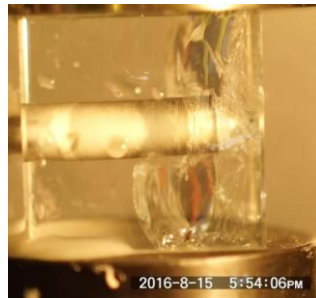
### Timing

Another feature of dynamic failure is its sudden occurrence and the high velocity in crack propagation. Figure 20 is a screenshot of a test sample under 70 kN loading, immediately before the occurrence of the dynamic failure.



**Figure 20: Test sample under 70 kN loading before burst**

Figure 21 is the screenshot of the same test sample at the moment of dynamic failure. It can be seen that the time shown on both figures is identical, which indicates that the dynamic failure occurred in less than 0.02 seconds (recording rate of 50 frames per second).



**Figure 21: Test sample bursting under 70 kN loading**

### Fracturing pattern

The analysis of the fracturing pattern is mainly focused on the following aspects:

- Level of concentration
- Fracturing pattern in vertical direction
- Fracturing pattern in horizontal direction

Figure 22 is the back view of the test sample under 70 kN loading. It can be seen from this figure that the fracturing is concentrated around the centre of drill hole and radiates out. The level of concentration is highest at the end of the borehole and reduces when propagating.



**Figure 22: Back view of test sample under 70 kN loading**

Figure 23 shows the back view of test sample under 130 kN loading. From these two figures it is evident that fracturing occurs along the vertical direction and there is no fracturing along the horizontal direction. The main reason for this pattern is the major principal stress. The sample fractures along the direction of loading and release the strain energy in that direction. As a result, all samples have a fracturing pattern along the vertical direction.



**Figure 23: Back view of test sample under 130 kN loading.**

## Drill Cuttings

The drill cuttings of the optical glass without any loading are shown in Figure 24. These cuttings are collected during the drilling process for UCS test preparation. It is evident that the cuttings are mostly powdery fine particles.



**Figure 24: Drilling cuttings without loading**

Figure 25 illustrates the drill cuttings collected after the 70 kN pre-loading test. From these two figures it is evident that the cuttings become blocky in the pre-loading tests. These blocky cuttings are mainly formed for two reasons:

- The glass powders agglomerate and form a small block due to the water for dust suppression during the test.
- The glass powders cover glass fragments and then agglomerate to form a small block



**Figure 25: Drilling cuttings after pre-loading test**

Inside the drill holes were also observed following the tests. In none-dynamic failure boreholes, the walls were very smooth and the hole diameter was highly consistent. In the cases where a dynamic failure occurred, the walls of the drill holes were fractured and failed resulting in uneven borehole walls. Unfortunately it was impossible to photograph these observations.

## CONCLUSION

As published by many authors in the past, the results from these experiments indicated that high stress is a contributing factor for stress driven dynamic failures. In the laboratory tests, dynamic failure does not occur until the loading reaches 70kN. The phenomenon of dynamic failure of the glass under high levels of uniaxial stress and loss of confinement during drilling is consistent with the finding of Babcock and Bickel (1984), which suggests that coals can be made to burst given necessary conditions of stress and constraint.

Another finding is that the dynamic failures occur in a short period of time which was less than 0.02 seconds in this testing environment. This conclusion validates the sudden characteristic of coal burst in its definition.



With respect to the fracturing pattern, cracking concentrates around the centre of drill hole and radiates out along the vertical direction which is the direction of major principal stress. This test result not only embodies the influence of major principal stress on coal burst but also validates the conclusion that high stress is a significant contributing factor for coal bursts.

It is also found that pre-existing cracks plays an important role in delaying or even eliminating the dynamic failures. During drilling, pre-existing cracks propagate rapidly towards the drill hole and lead to the stress being transferred along the crack. Strain energy therefore cannot be accumulated and the stress cannot be concentrated in front of the drill hole to trigger a dynamic failure. This observation can validate the effectiveness of destress drilling in coal burst prevention.

### ACKNOWLEDGEMENTS

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